Effect of wind speed on columnar aerosol optical properties at Midway Island

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[1] Aerosol optical properties over Midway Island in the central Pacific Ocean are considered in conjunction with the information on surface wind speed. In general, optical conditions over Midway resemble aerosol found over other maritime locations in the Pacific Ocean (Lanai, Tahiti, and Nauru). The most frequently occurring values of aerosol optical depth at 500-nm wavelength and Angstrom parameter are 0.06 and ~0.40, respectively. Empirical relationships are established between columnar aerosol optical properties and surface wind speed. Increased emission of sea-salt aerosols at greater wind speeds primarily influenced aerosol optical depth at infrared wavelengths. The correlation coefficient between 24 hour average surface wind speed and aerosol optical depth, although not high (0.52 at a 1020 nm wavelength), is statistically significant at a 99% confidence level. Wind speed anticorrelates with the Angstrom parameter owing to an influx of large particles from the surface. Wind speed influences primarily the coarse fraction (radius > 0.5 μm) concentration of the retrieved columnar size distribution (correlation coefficient 0.56). Effective radii of the retrieved fine and coarse modes are found to be independent of wind speed. Average size distributions for various wind speed bins can be very well simulated with the maritime aerosol component model. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 1640 Global Change: Remote sensing; 4548 Oceanography: Physical: Ocean fog and aerosols; *KEYWORDS:* aerosol optical depth, maritime aerosol, wind speed, atmospheric correction, AERONET

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1. Introduction

[2] The World Ocean covers approximately 70% of Earth's surface and is one of the major sources of natural aerosols. Aerosol production sources and various factors determining aerosol spatial and temporal distribution are important for understanding the Earth radiation budget, visibility changes and aerosol-cloud interactions [*Latham and Smith*, 1990; *Bigg et al.*, 1995; *Murphy et al.*, 1998; *Haywood et al.*, 1999; *King et al.*, 1999; *Kaufman et al.*, 2002]. In order to achieve desired accuracy in atmospheric correction algorithms the appropriate level of aerosol modeling is critical [*Gordon*, 1997]. Atmospheric aerosol is a complex dynamic system with temporal variability caused by synoptic (air mass change) and other meteorological factors, and/or variability in source and sink processes. The state of aerosol at an observation point is also subject to significant variations owing to diurnal changes in the radiative regime, turbulence and thermodynamic characteristics.

[3] The effect of wind speed on the concentration and size distribution of aerosols over the oceans was comprehensively studied during the last several decades. A number of excellent reviews have been published [see, e.g., *Blanchard and Woodcock*, 1980; *Podzimek*, 1980; *Fitzgerald*, 1991; *O'Dowd et al.*, 1997; *Gong et al.*, 1997; *Andreas*, 1998; *Heintzenberg et al.*, 2000; *Lewis and Schwartz*, 2001]. Definite correlation was found between surface wind speed and sea-salt aerosol concentration (for various size ranges and for total). However, only part of the variance could be explained by the current wind speed. Considerable scatter remains because of a few days residence time of aerosols and other factors, for example, advection and vertical mixing [*Quinn and Coffman*, 1999].

[4] *Hoppel et al.* [1990] reported that aerosol scattering coefficients measured at the ship deck level have a stronger dependence on wind speed at infrared wavelengths. They normalized their measured values to a relative humidity of 75%, however considerable scatter remained in the data despite the removal of relative humidity effects. This scatter could at least, in part, be attributable to variations in air mass history [*Hoppel et al.*, 1990]. The general dependence of lidar- derived near-surface extinction coefficients on surface

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wind speed [*Flamant et al.*, 1998] favorably agrees with *Hoppel et al.* [1990]. Recent measurements conducted at a coastal station (Mace Head, Ireland) [*Kleefeld et al.*, 2002] indicated that air mass origin defines atmospheric optical state for moderate wind speeds. With increasing wind speed (especially in the marine air masses) the sea-spray production process gets more pronounced and scattering coefficients exhibit an increase. According to *Kleefeld et al.* [2002] about 20% of the scattering coefficient variability can be explained by variations in the local wind speed.

[5] The influence of wind speed on aerosol optical depth in the whole atmospheric column is a much more difficult problem [*Platt and Patterson*, 1986; *Villevalde et al.*, 1994; *Smirnov et al.*, 1995; *Moorthy et al.*, 1997; *Kusmierczyk-Michulec et al.*, 1999]. A link between optical turbidity and particle generation by wind is not easy to detect, since it can be masked by the background aerosol (of continental origin in coastal areas, for example). Accordingly surface generation effects can be clearly noticed only when measurements are taken in a reasonably transparent atmosphere. Ideally a relationship between spectral aerosol optical depth ($\tau_a(\lambda)$) and wind speed needs to be ascertained in the same air mass in order to minimize the influence of other meteorological parameters on optical properties or when all meteorological parameters are simply the same over the range of wind speeds considered. Discriminating between air masses permits a more rigorous analysis of the link between wind speed and optical depth [*Smirnov et al.*, 1995]. The correlations of $\tau_a(\lambda)$ versus wind speed in maritime tropical air masses were found to be significantly better than those obtained in a study of the same Pacific Ocean data [*Villevalde et al.*, 1994], where no air mass discrimination was made. This means that the correlation coefficient increased when the data were effectively characterized by more uniform atmospheric conditions.

[6] In the current paper we analyze aerosol optical properties over Midway Island in the subtropical Pacific Ocean in conjunction with information on surface wind speed. More than one year of data ($\sim$14 months) is considered. Because of the unique location of Midway (very far from continental landmasses and almost in the middle of the northern Pacific Ocean) air that reaches it spends enough time over the ocean to be dominated by oceanic sources, at least in the vast majority of cases.

2. Analysis

[7] The Aerosol Robotic Network (AERONET) has been operational for more than 10 years (since May 1993). It deploys standardized instrumentation (automatic Sun and sky scanning radiometers CIMEL), measurement protocol, data processing, cloud-screening algorithm, and inversion techniques to retrieve information on columnar aerosol characteristics [*Holben et al.*, 1998, 2001; *Eck et al.*, 1999; *Smirnov et al.*, 2000; *Dubovik and King*, 2000; *Dubovik et al.*, 2000].

[8] Aerosol optical properties were derived from direct Sun and sky radiation measurements performed at the operational AERONET site on Midway Island. Midway Island is situated in the northwestern Pacific Ocean at 28°12′N and 177°22′W almost equidistant from the United States and Japan ($\sim$4,500 km from San Francisco and

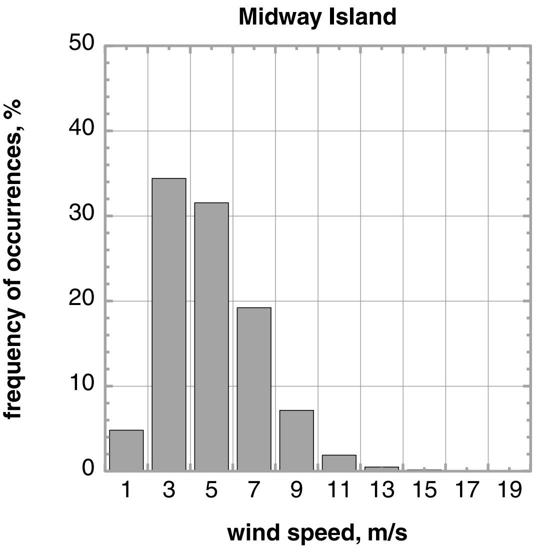

Figure 1. Frequency of occurrences of the hourly averaged surface wind speed.

3,500 km from Japan). Midway is actually consists of two islands, the larger one (Sand Island) has a total land area of $\sim$6 km^2 and we will refer to it in this paper as "Midway Island." The climate on Midway can be considered semi-tropical. The weather is generally uniform throughout the year nevertheless there are two distinct seasons, winter, between January and March, and summer, between July and October. Midway summers are slightly less humid and relative humidity shows smaller day-by-day variations. Average high temperature for the summer months is $\sim$27°C and for the winter months is 21°C. Winds can blow severely at times, however during the whole measurement period (from January 2001 through February 2002) only about 3% of the hourly averaged surface winds exceeded 10 m/s (see Figure 1). Surface relative humidity frequency of occurrences peaks at $\sim$75% for the hourly averaged and daytime averaged values. Wind speed and water vapor pressure information was obtained from National Climatic Data Center (Asheville, North Carolina).

[9] Because of its small area and flat surface (elevation $\sim$4 m) Midway is an ideal site for investigating aerosol optical properties over the oceans. If using a ship is the correct way of studying aerosols over the oceans then Midway can be considered a stationary platform, which in a sense looks like a large ship deck.

[10] The Sun/sky radiometer deployed on Midway had eight spectral channels between 340 and 1020 nm (340, 380, 440, 500, 670, 870, 940 and 1020 nm). The 940 nm data is used for the columnar water vapor content estimations. Diffuse sky radiances in the solar almucantar are acquired at 440, 670, 870 and 1020 nm wavelengths. Typical total uncertainty in the spectral aerosol optical depth (derived from the direct Sun measurements) $\tau_a(\lambda)$ for a field instrument is $\pm0.01-0.02$ and is spectrally dependent with the higher errors (±0.02) in the UV spectral range [*Eck et al.*, 1999].

[11] Figure 2a illustrates the daily averaged aerosol optical depth at 500 nm plotted versus columnar water vapor content. Long-ranged transport of Asian aerosols elevated

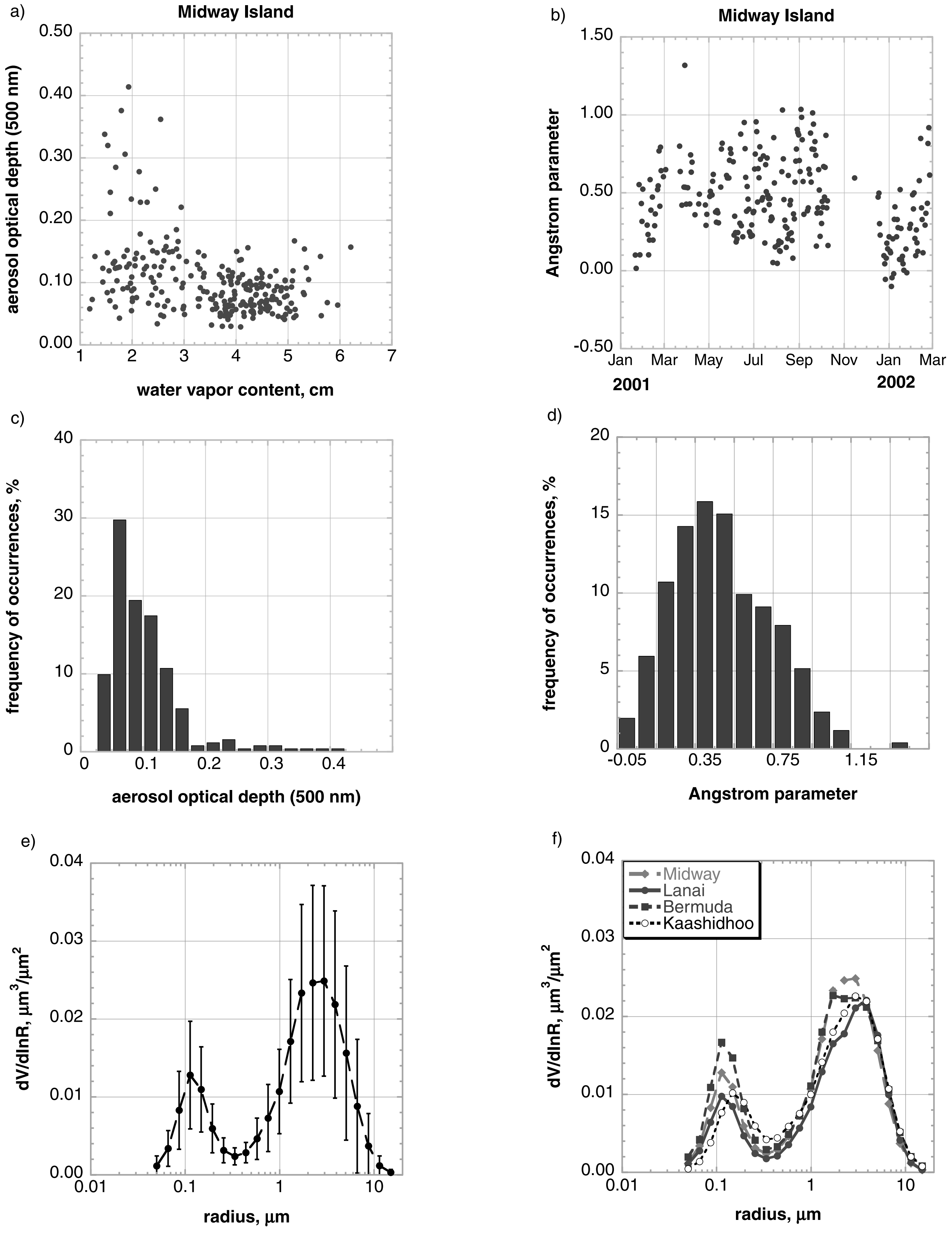

Figure 2. Midway Island, Pacific Ocean. (a) Mean daily values of aerosol optical depth at 500 nm versus columnar water vapor content; (b) mean daily values of Angstrom parameter; (c) frequency of occurrences of aerosol optical depth at 500 nm; (d) frequency of occurrences of Angstrom parameter; (e) average aerosol volume size distribution in the total column; and (f) average columnar volume size distribution for Midway and maritime components for Lanai, Bermuda, Kaashidhoo.

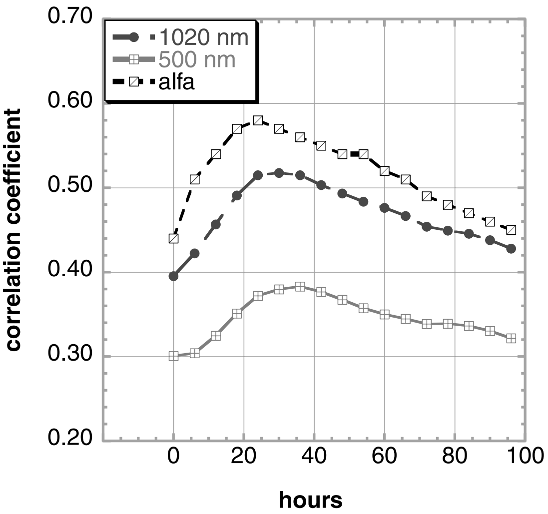

Figure 3. Correlation coefficients between various aerosol optical parameters and wind speeds.

daily averages above τ_a(500 nm) ~0.20 on 15 days out of 252 days of measurements. On some of those days satellite imagery from TOMS supported our conclusions. In the analysis of the influence of wind speed on optical parameters we will not consider those 15 days when τ_a(500 nm) was higher than 0.20. The Angstrom parameter α (derived from a multispectral log linear fit to the equation $\tau_a \sim \lambda^{-\alpha}$ in the range 440–870 nm) is typically below 1, which indicates that coarse particles (smaller α) always influence atmospheric aerosol optical properties over Midway (Figure 2b). The frequency histogram of τ_a(500 nm), given in Figure 2c, shows a peak at ~0.06–0.07 similar to the other Pacific island sites (Lanai, Tahiti, Nauru) [*Smirnov et al.*, 2002]. The Angstrom parameter frequency distribution for Midway shows relatively neutral spectral dependence of optical depth with the modal value below 0.50, which is a clear indication of the enrichment of maritime air by sea-spray aerosol components.

[12] For the whole analyzing period (January 2001–February 2002) 176 instantaneous retrievals satisfied the residual error threshold less than 5% (between computed and measured sky radiances) and the number of scattering angles in the measured sky radiance distributions was not less than 21 [*Dubovik et al.*, 2002]. After we eliminated retrievals with possible dust contamination the number of instantaneous retrievals contributing to the statistics was 171. The average aerosol volume size distribution retrieved from the Sun and sky radiance measurements is presented on Figure 2e. Variability of the size distribution can also be seen in Figure 2e where the vertical error bars show one standard deviation from the average value. Figure 2f reveals a lot of similarity among "maritime" columnar size distributions for Bermuda, Lanai, Kaashidhoo [*Smirnov et al.*, 2003] and Midway.

[13] Wind speed determines sea-state (wave height, whitecaps etc.) and various formulations for the sea-salt aerosol generation functions use current wind speed or average wind speed over a previous time period [*Gathman*, 1983; *Hoppel et al.*, 1990; *Andreas*, 1998; *Flamant et al.*, 1998; *Hoppel et al.*, 2002]. Correlation coefficients at Midway between various instantaneous measured aerosol optical parameters and current or averaged wind speeds are presented in Figure 3. Wind speeds were averaged over time periods ranging from one to 96 hours. Correlations with the current simultaneous wind speed are shown as 0 hours. One can observe that correlation coefficients have maximum close to 24 hours. In the further analysis we will consider surface wind speed averaged within 24 hours prior the instantaneous optical measurement.

[14] Figures 4a and 4b illustrate regressions between wind speed and aerosol optical depth at wavelengths 1020 nm and 500 nm. More than 5200 instantaneous aerosol optical depth measurements contributed to the statistics presented. Our measurements show a stronger dependence (higher regression slope, higher correlation coefficient) for aerosol optical depth versus wind speed in the IR spectral range. Because the wind generated sea-salt particles have radii higher than 0.5 μm [see, e.g., *Blanchard and Woodcock*, 1980] the greater sensitivity of the optical properties in the IR is expected [*Hoppel et al.*, 2002, 1990]. The correlation coefficient between τ_a(1020 nm) and wind speed is 0.52 (Figure 4a and Table 1). This value, although not high, is statistically significant at a 99% confidence level. In the midvisible the correlation coefficient is 0.37 (Figure 4b and Table 1), while in the UV it diminishes to ~0.30, showing the expected trend in the wind speed influence on spectral optical depth due to a greater influence of fine mode particles on shorter wavelength optical depth. An influx of large particles is responsible, at least in part, for the anticorrelation between wind speed and the Angstrom parameter α (Figure 4c). A statistically significant negative correlation (0.58) between α and wind speed gives further indirect evidence of the effects of wind speed on the aerosol size distribution.

[15] In support of the arguments for our analysis, we would like to note that complete exclusion of the data acquired during the expected spring peak in dust concentration over Midway (February–May) slightly increased correlations coefficients between optical parameters and wind speed and did not change the conclusions. Correlations of the daily averaged optical depth and wind speed were found to be within several percent from the listed on Figure 4. It proves the robustness of our conclusions.

[16] Our measurements are consistent with previously reported results. Ship-based measurements [*Villevalde et al.*, 1994; *Smirnov et al.*, 1995] showed slope increase with wavelength increase for τ_a versus wind speed relationships. Slopes, however, are lower than in the current consideration (Table 1). Angstrom parameter decrease with the wind is also coherent with the current work (Figure 4c and Table 1). The slope of the linear fit to the measurements on Cape Grim [*Wilson and Forgan*, 2002] is very close to the results of *Platt and Patterson* [1986] for the same region. Table 1 also presents linear fits (for the wind speed lesser than 10 m/s) to the optical depth data reported by *Moorthy et al.* [1997] and *Satheesh et al.* [1999]. In the latter case, however, a major contributor of aerosol loading was anthropogenic aerosol from the Indian subcontinent and not by the sea surface.

[17] The linear fit to Hoppel et al.'s surface level extinction measurements (given by the formula on Figure 29 in the work of *Hoppel et al.* [1990]) for 12-hour average wind

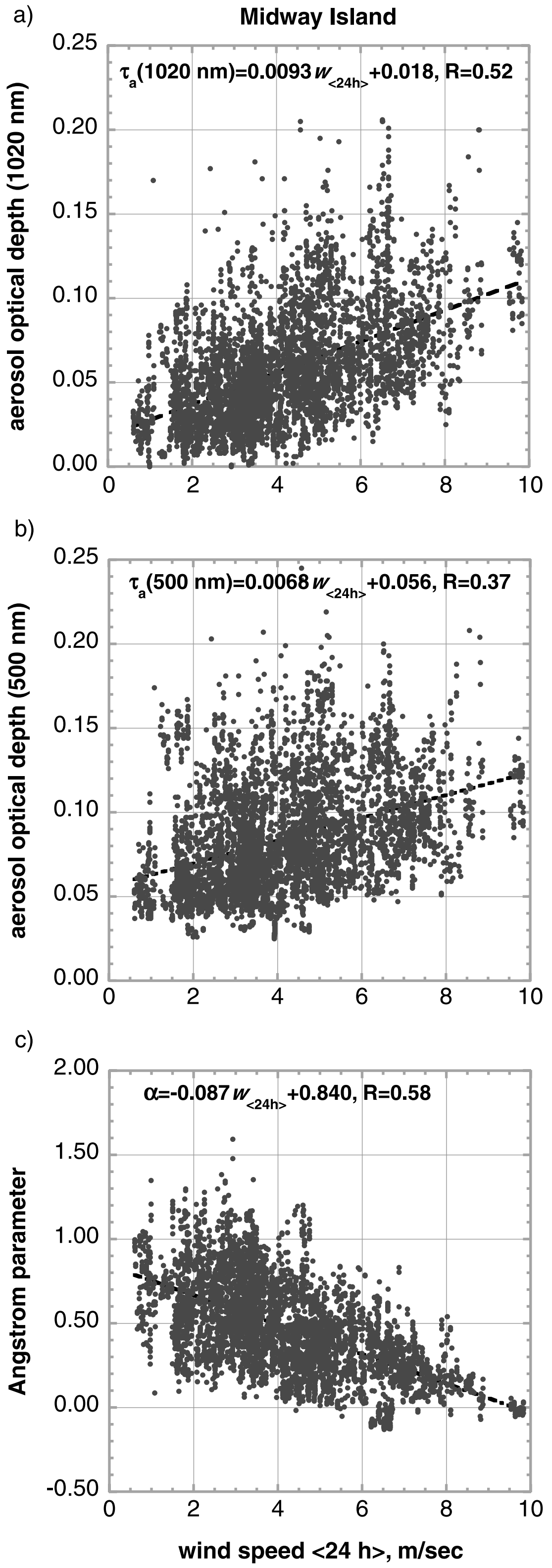

Figure 4. Scattergrams of aerosol optical depth at (a) 1020 nm, (b) 500 nm, and (c) Angstrom parameter versus the surface wind speed averaged over a 24-hour period.

speed less than 10 m/s yielded a slightly higher slope than our analysis of Midway data for the total atmospheric column. *Flamant et al.* [1998] presented results similar to *Hoppel et al.* [1990]. Linear fit coefficients for wind speeds less than 10 m/s are also listed in Table 1. We would expect having slope coefficients slightly lower for the columnar optical depth than for the near-surface extinction measurements because of the generation and dispersion/removal of aerosols [*Gong et al.*, 2002].

[18] Aerosol volume size distributions in the total atmospheric column were retrieved from Sun and sky radiance measurements according to *Dubovik and King* [2000]. Evidence of two fractions (fine and coarse) in the retrievals (Figure 2e) allowed separate consideration of each mode in conjunction with the wind speed. Figure 5a presents concentrations in the total column versus wind speed. For each mode the columnar volume of particles per unit cross section of atmospheric column ($\mu m^3/\mu m^2$) is defined as:

$$Cv = \int_{r_{\min}}^{r_{\max}} \frac{dV(r)}{d\ln r} d\ln r.$$

[19] Wind speed influences primarily the coarse fraction ($r > 0.5$ μm) concentration of the retrieved columnar size distribution (correlation coefficient 0.56). For the fine mode (radii range 0.05–0.5 μm) the correlation is much weaker, in full agreement with the experimental [*Hoppel et al.*, 1990] and model studies [*Gong et al.*, 1997]. The effective radius for each mode (defined as a ratio of the third over the second moment of the size distribution) has been found not to be wind speed dependent (Figure 5b).

[20] Note that parameters presented on Figure 5b are not associated with particular relative humidity levels and describe size distributions in ambient conditions. We attempted adjusting Reff presented for the "ambient" conditions to the so-called "dry" conditions, based on the surface measurements of relative humidity, following *Gasso et al.* [2000]. It did not improve correlation with wind speed. We also used a correction factor presented by *Flamant et al.* [1998] to normalize the extinction coefficient to a relative humidity of 60% and plot it versus wind speed. Correlation coefficient remained about the same, however. This underlines again the complexity of the relationship between columnar and near-surface measured parameters. Generally speaking, we may or may not find agreement between columnar retrievals and in situ measurements. AERONET measures optical characteristics in its ambient state at the ambient relative humidity. The aerosol concentration profile and relative humidity profile are not known and therefore any humidity related adjustments are problematic. On the other hand methodological and instrumental biases of the in situ measurement technique [*Reid et al.*, 2003] inhibit direct comparisons of size distributions.

[21] Several useful regression relationships are listed in the bottom part of Table 1. The range of aerosol optical depth variability over Midway is not wide, compared to continental sites [*Holben et al.*, 2001]. Nevertheless, strong correlations have been found between retrieved columnar volume concentrations and aerosol optical depth. Note, that regression coefficient for the fine mode volume concentration is smaller than reported by *Dubovik et al.* [2002] for Lanai. It reflects the fact that the coarse fraction dominated

Table 1. Regression Statistics of Optical Parameters Versus Wind Speed

	a	*b*	*R*corr	Reference
τ_a(500 nm) = $a*w_{\langle 24h\rangle}+b$	0.0068	0.056	0.37	current work
τ_a(1020 nm) = $a*w_{\langle 24h\rangle}+b$	0.0093	0.018	0.52	
$\alpha = a*w_{\langle 24h\rangle}+b$	−0.087	0.840	0.58	
τ_a(500 nm) = $a*w$+b	0.0028	0.046	. . .	*Platt and Patterson* [1986]
τ_a(500 nm) = $a*w$+b	0.0033	0.101	0.29	*Villevalde et al.* [1994]
τ_a(1640 nm) = $a*w$+b	0.0048	0.077	0.38	
τ_a(500 nm) = $a*w$+b	0.0036	0.123	0.25	*Smirnov et al.* [1995]
τ_a(1020 nm) = $a*w$+b	0.0062	0.061	0.51	
τ_a(1640 nm) = $a*w$+b	0.0075	0.079	0.60	
$\alpha = a*w$+b	−0.046	0.837	0.57	
		Linear Fit to the Measurements by Moorthy et al., Satheesh et al., and Wilson and Forgan		
τ_a(500 nm) = $a*w_{\langle daily\rangle}$+b	0.0183	0.025	. . .	*Moorthy et al.* [1997]
τ_a(1020 nm) = $a*w_{\langle daily\rangle}$+b	0.0379	0.047	. . .	
τ_a(500 nm) = $a*w$+b	0.0084	0.122	. . .	*Satheesh et al.* [1999]
τ_a(1020 nm) = $a*w$+b	0.0021	0.029	. . .	
τ_a(500 nm) = $a*w$+b	0.0035	−0.006	. . .	*Wilson and Forgan* [2002]
		Linear Fit to the Measurements by Hoppel et al. and Flamant et al.		
σ_a(500 nm) = $a*w_{\langle 12h\rangle}$+b	0.0125	0.003	. . .	*Hoppel et al.* [1990]
σ_a(500 nm) = $a*w_{\langle 12h\rangle}$+b	0.0202	0.051	. . .	*Flamant et al.* [1998]
σ_a(500 nm) = $a*w_{\langle 12h\rangle}$+b	0.0186	0.036	. . .	
		Some Additional Relations		
Cv(coarse) = $a*w_{\langle 24h\rangle}+b$	0.0073	0.014	0.56	current work
Cv(total) = $a*w_{\langle 24h\rangle}+b$	0.0077	0.027	0.51	
Reff(fine) = $a*w_{\langle 24h\rangle}+b$	0.0000	0.125	0.00	
Reff(coarse) = $a*w_{\langle 24h\rangle}+b$	0.0060	1.918	0.03	
Cv(coarse)/Cv(fine) = $a*w_{\langle 24h\rangle}+b$	0.529	1.344	0.47	
Cv(fine) = $a*\tau_a$(500 nm)+b	0.140	0.002	0.77	
Cv(coarse) = $a*\tau_a$(500 nm)+b	0.501	0.004	0.80	
Cv(fine) = $a*\tau_a$(1020 nm)+b	0.136	0.007	0.58	
Cv(coarse) = $a*\tau_a$(1020 nm)+b	0.723	0.006	0.90	

the volume aerosol size distribution and therefore optical conditions over Midway were "truly maritime."

[22] Aerosol volume size distributions retrieved from the Sun/sky radiances can be averaged within several wind speed bins and averaged size distributions for wind speed ranges 0–4 m/s, 4–6 m/s and 6–8 m/s have been plotted in Figure 6a in order to show aerosol dynamics. The fine mode shows relative stability, while the coarse fraction changes significantly. Computed for these three wind speed bins averaged aerosol optical depth and Angstrom parameter

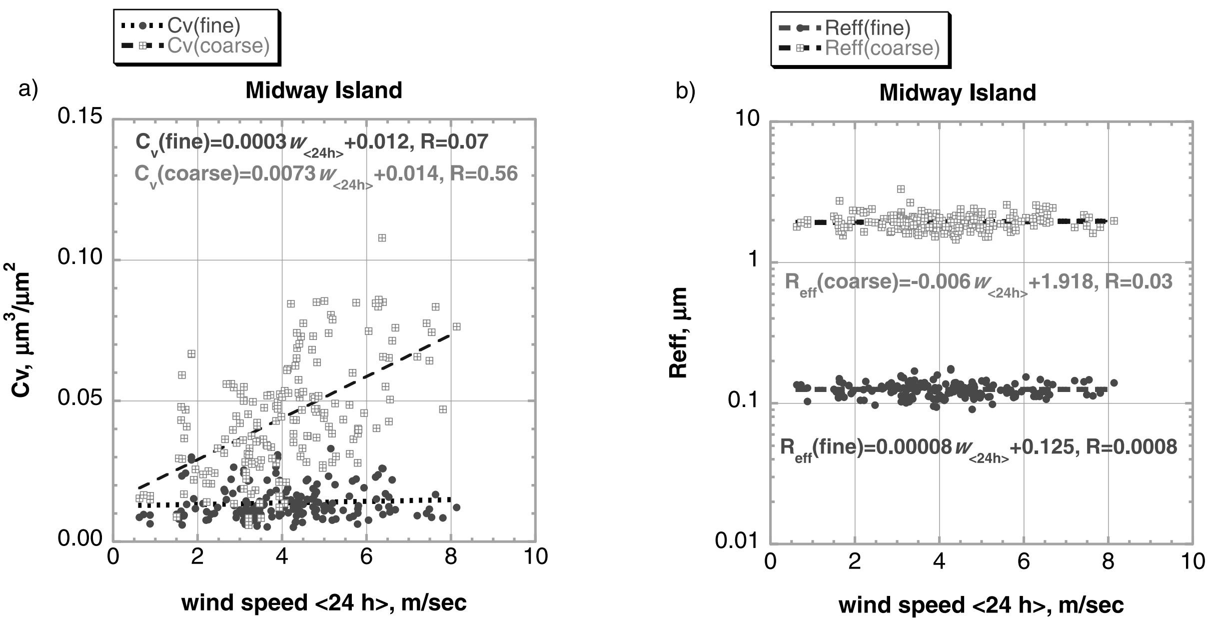

Figure 5. (a) Scattergrams of the fractional (fine and coarse) columnar volume of particles per unit cross-section of atmospheric column and (b) the effective radius of each fraction versus the surface wind speed averaged over a 24-hour period.

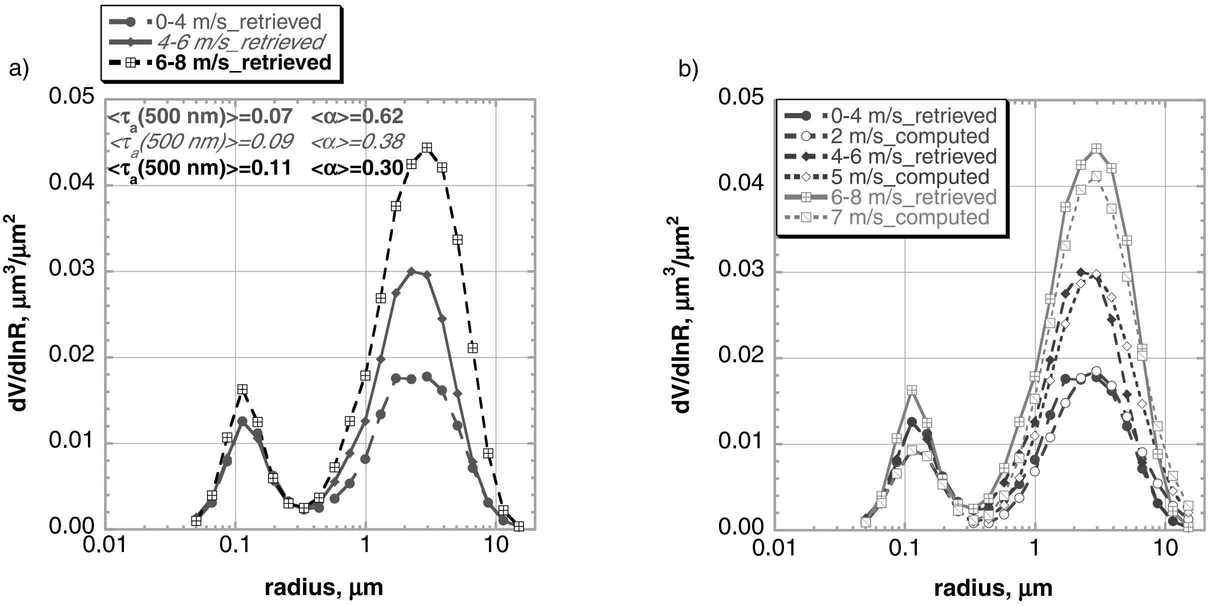

Figure 6. (a) Averaged size distributions for wind speed ranges 0–4 m/s, 4–6 m/s and 6–8 m/s; and (b) averaged and simulated using maritime aerosol component model size distributions.

values are 0.07, 0.09, 0.11 and 0.62, 0.38, 0.30 respectively. The first pair (0.07 and 0.62) corresponds approximately to the wind speed of 2 m/s and is very similar to the optical parameters for the maritime aerosol component model based mainly on the Lanai AERONET data [*Smirnov et al.*, 2003].

[23] *Smirnov et al.* [2003] suggested a maritime aerosol model, which can be used to define the maritime component of marine air masses or in combination with other various aerosol types (dust, biomass burning etc.). To illustrate the applicability of the maritime model to the results obtained on Midway we will try including wind speed as an additional parameter in order to add dynamics into the maritime component model. Let us make several assumptions. We consider only the volume concentration of the coarse mode to be wind speed dependent, which is supported by the analysis shown in Figure 6a. Choosing wind speed of 2 m/s as a starting point for maritime model size distribution [*Smirnov et al.*, 2003] we will assume that the fine mode stays constant and Cv(coarse) increases as a function of wind speed proportionally according to the empirical relationship reported by *Lovett* [1978]. In order to account for the difference between surface and column loading we multiplied Cv(coarse) by a factor of 1.46/1.68 for Tropical Pacific following *Gong et al.* [2002].

[24] The simulation results that are shown in Figure 6b illustrate how the mean size distributions can be fitted with the resulting dynamic maritime component model. The agreement shown is rather remarkable.

3. Conclusions

[25] The principal conclusions drawn from our work can be summarized as follows:

[26] 1. Atmospheric aerosol optical properties over Midway Island are very similar to the other Pacific sites (Lanai, Nauru, Tahiti) with the most frequent τ_a(500 nm) ~0.06 and Angstrom parameter $\alpha \sim 0.40$.

[27] 2. A link was established between directly measured aerosol optical parameters and 24 hour averaged surface wind speed. Increased wind speed emission of sea-salt aerosols influenced most strongly the aerosol optical depth at infrared wavelengths. Aerosol optical depth at the 1020-nm wavelength has a significant dependence on wind speed (correlation coefficient of 0.52 is statistically significant at a 99% confidence level). The influx of the large particles causes the Angstrom parameter α to anticorrelate with the wind speed (correlation coefficient of −0.58 is statistically significant at a 99% confidence level).

[28] 3. Columnar aerosol volume concentration (retrieved from the direct Sun and diffuse sky radiances) of the coarse mode is found to be very well correlated with 24 hour averaged wind speed (r = 0.56).

[29] 4. Within the wind speed range considered the effective radii of the fine and coarse fractions of the retrieved columnar size distributions are independent of wind speed.

[30] 5. Averaged within various wind speed ranges the aerosol size distributions over Midway can be reasonably well predicted with a maritime aerosol component model that combines elements of both remotely sensed and in situ [*Lovett*, 1978] relationships of oceanic aerosols.

[31] We note that in considering some other island sites of the AERONET network (Lanai, Nauru, Tahiti, Ascension Island) we did not find any significant correlation between optical parameters and wind speed. Correlation coefficients between optical depth at a 1020-nm wavelength and wind speed are ~0.10–0.20, being slightly lower for the 500-nm channel. The Angstrom parameter α at all of those sites showed to some extent the same trend as over Midway with the correlation coefficients a little over 0.20. A variety of factors can mask the correlation, for example, narrow range of wind speeds, mountainous terrain, nonuniform meteorological conditions, island aerosol influence, etc. Even attempts at elimination of possible volcanic, dust and

biomass burning residual aerosol contamination did not make the correlations any stronger at those sites.

[32] Recently a new and potentially very promising AERONET site has been established near the ‘‘roaring forties’’ of the Southern Hemisphere (Amsterdam Island). After a number of years of data collection it will perhaps offer a more comprehensive data set to consider, especially for the conditions of very high wind speeds (over 10 m/s).

[33] **Acknowledgments.** The authors thank Michael King of the EOS Project Science Office for his support of AERONET. We thank Dennis Clark, NOAA for providing the MOBY wind speed data. We also thank two anonymous reviewers for useful questions and suggestions.

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